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Towards Prioritizing Flexibility in the Design and Construction of Concentrating Solar Power Plants

Monika Topel^{1, a)}, Mårten Lundqvist¹, Fredrik Haglind² and Björn Laumert¹

¹*Brinellvägen 68, Department of Energy Technology, KTH Royal Institute of Technology, SE 100-44, Stockholm*

²*Department of Mechanical Engineering, DTU Technical University of Denmark, 2800 Kgs. Lyngby, Denmark.*

^{a)} Corresponding author: monika.topel@energy.kth.se

Abstract. In the operation and maintenance of concentrating solar power plants, high operational flexibility is required in order to withstand the variability from the inherent solar fluctuations. However, during the development phases of a solar thermal plant, this important objective is overlooked as a relevant factor for cost reduction in the long term. This paper will show the value of including flexibility aspects in the design of a concentrating solar power plant by breaking down their potential favorable impact on the levelized cost of electricity (LCOE) calculations. For this, three scenarios to include flexibility as a design objective are analyzed and their potential impact on the LCOE is quantified. The scenarios were modeled and analyzed using a techno-economic model of a direct steam generation solar tower power plant. Sensitivity studies were carried out for each scenario, in which the level of improvement due to each scenario was compared to the base case. Then, the results obtained for each scenario were compared for similar levels of LCOE and flexibility improvements. In general, all scenarios were beneficial on power plant performance. Improvements on the LCOE in the range of 3-4% were obtained with different distributions of costs and annual electricity for each case.

INTRODUCTION

The development of concentrating solar power plants (CSPPs) is defined through tendering 1. Once a solar tender is launched, industries in the field bid complying with the specifications. The consortium that procures a tender becomes the solar project owner and signs a power purchase agreement with the government. This marks the beginning of the CSPP development process shown in **FIGURE 1**. In general, the design and construction of CSPPs involves complex decision making that must take into account several objectives like performance, operability, safety, reliability and profitability. Previous work has demonstrated that no single optimum configuration can be found meeting all objectives 2, but instead it is possible to analyze trade-off curves of multiple optimum designs. Still, the complexity remains by the fact that these objectives are valued differently by the main players that interact throughout the process, as indicated in **FIGURE 1**.

Operation and maintenance is one of the critical factors that drive a CSPP to realize projected contracted load and revenues 3. In CSPP operation and maintenance, high operational flexibility is required in order to withstand the variability from the inherent solar fluctuations. However, given the contractual structure displayed in **FIGURE 1**, investment decisions related to component flexibility and plant operability are not taken by the same player who owns or eventually operates the plant. As such, these important objectives are overlooked during the design and construction phases as relevant factors for cost reduction in the long term. Flexibility is the ability of the power plant to perform satisfactorily under conditions different from nominal design. A key aspect for CSPP flexibility is the capability for fast starts in order to harvest the solar energy as soon as it becomes available. This paper will show the value of including flexibility aspects in the development process of a CSPP by breaking down their potential favorable impact on the resulting LCOE.

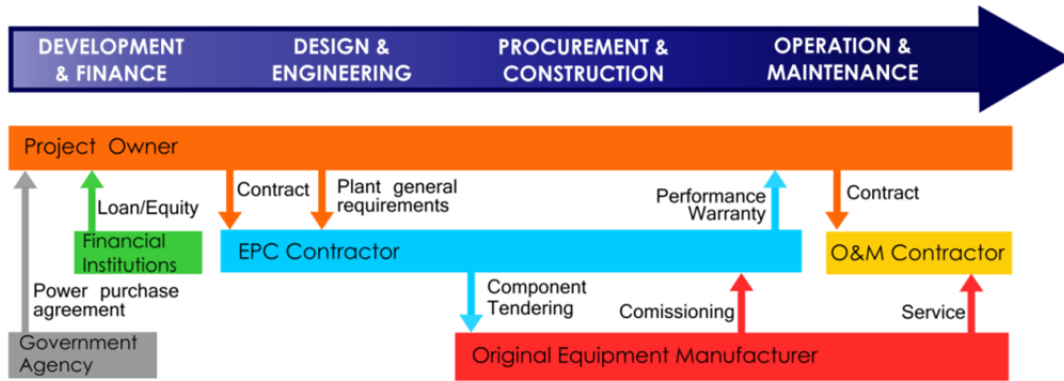


FIGURE 1. Development process and players involved in the value chain of a CSPP project.

In order to accomplish this, three scenarios to include flexibility as a design objective are analyzed and their potential impact on the LCOE is quantified. The first scenario evaluates the benefits of procuring a component with faster ramping rates in exchange for a higher capital investment (CAPEX). The second scenario considers the implementation of retrofitting measures to already existing components in order to improve their transient operation. Finally, the third scenario makes an assessment on the added value of contracting service and maintenance agreements that offer increased operational flexibility of the power plant components. Sensitivity studies were carried out for each scenario, in which the level of improvement due to each scenario was compared to the base case. Then, the scenarios were compared for similar levels of LCOE and flexibility improvements.

Nomenclature			
ACC	Air cooled condenser	HPT	High pressure turbine
CAPEX	Capital expenditures	LCOE	Levelized cost of electricity
CSPP	Concentrating solar power plant	LPT	Low pressure turbine
D	Deaerator	NOH	Normal operating hours
DSG	Direct steam generation	OEM	Original equipment manufacturer
EOH	Equivalent operating hours	OPEX	Operating expenditures
EV	Evaporator	RH	Reheater
HB	Heat Blanket	SH	Superheater

POWER PLANT TECHNO-ECONOMIC MODEL

The analysis on the value of flexibility was performed using DYESOFT, a techno-economic modeling tool developed at KTH 45. A flowchart with the modeling scheme and input parameters of DYESOFT is shown in **FIGURE 2**, where the required input data is represented in rhomboids of different colors depending on the nature of the data: design configuration (dark grey), location related (light grey) and cost functions (white). Additionally, the main processes and calculation steps are shown in white rectangles.

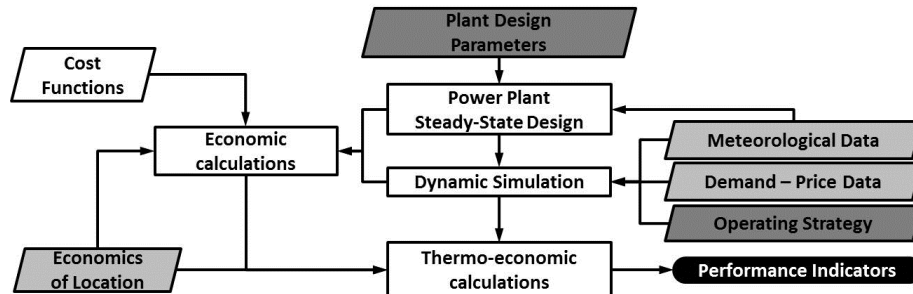


FIGURE 2. Schematics of information flow in DYESOFT.

A direct steam generation solar tower power plant (DSG-STPP) was selected as the object of study in this work. The DYESOFT model development of such DSG-STPP configuration has been performed and described in previous

work by the authors 6. A representative layout of the modeled power plant is shown in **FIGURE 3**. In general, the configuration consist of a Rankine reheat cycle, with high and low pressure turbine units (HPT and LPT), and air cooled condenser (ACC) and a deaerator (D) on the cold side. In addition the steam generation components, evaporator (EV), super-heater (SH) and re-heater (RH), form the central receiver at the top the tower. The main design parameters and configuration specifications of the DSG-STPP used as the base case for this work are shown in **TABLE 1** . For the purpose of the studies carried out in this work, the fact that the selected plant configuration does not comprise thermal energy storage serves to observe the impact and value of operational flexibility more clearly for each of the flexibility scenarios considered. For this same reason, no fossil fuel back-up firing was taken into account for the operation of the plant.

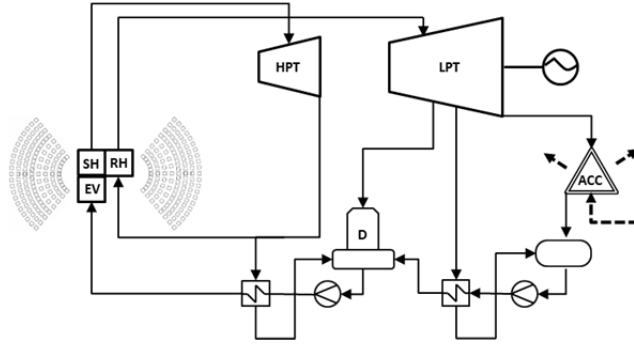


FIGURE 3. Schematic layout of the modeled direct steam generation solar tower power plant.

TABLE 1. DSG-STPP design specifications.

Design Specifications			
Location	Daggett, California	Power Cycle	Steam Rankine
Solar Field Type	Surround	Turbine capacity	126 MW
Heat transfer fluid	Water	Turbine inlet temperature	565 °C
Solar field aperture area	864.510 m ²	Power cycle pressure	160 bar
Heliostat aperture area	15 m ²	Number of extractions	4
Tower height	122 m	Cooling Method	Dry

Modeling Flexibility Improvements

In order to be able to observe the changes in power plant thermo-economic performance due improvements in O&M flexibility, the reference DYESOPT DSG-STPP model mentioned above was modified. These changes were made to accommodate the flexibility scenarios described previously and they involved adjusting cost functions and including additional design parameters in order to be able to capture the improvements in plant flexibility in both the technical and economic performances. The modifications to the model are described below in accordance to each of the scenarios considered on this work.

Scenario I: Procurement of Steam Turbine with Faster Start-up Rates

This scenario is applicable to the situation in which the CSPP is under construction and the EPC contractor is in the process of tendering the respective equipment from the turbine OEMs. At this stage, the plant is yet to be built and operated, the technical performance of the turbine and its CAPEX are the main decision variables. As such, the modeling aims to quantify the impact on the LCOE of the CSPP when selecting a turbine that has been designed with faster start-up rates and as a consequence of that is also more expensive. In order to model a turbine designed with faster ramp rates, an input variable, *flex*, was introduced to scale the reference start-up times of the turbine modeled within the DSG-STTP. These times are ruled by start-up curves provided by the turbine manufacturer with the aim of ensuring the safe operation of the machine with regards to its designed lifetime. As such, whenever *flex* is varied within the range of [0.1 1], the respective design cold, warm and hot start-up curves of the turbine are scaled to a shorter time. Analogously, in order to also capture the difference in price due to the increased flexibility, this same input variable was included within the existing cost function of the steam turbine component 7. This cost

function is shown in Eq. (1) which originally takes into account the power of the turbine W , the isentropic efficiency η_s , and the inlet temperature T_{in} . The influence of $flex$ and its respective exponent A was included in this work and its influence in the overall costs and performance of the DSG-STPP will be evaluated in the results section.

$$C_{ST}^{CAPEX} = c_{turbine}^{REF} \cdot W^{0.7} \cdot \left(1 + \frac{0.05}{1 - \eta_s}\right)^3 \cdot \left(1 + 5e^{\frac{T_{in} - 866K}{10.42K}}\right) \cdot \left(\frac{1}{flex}\right)^A \quad (1)$$

Scenario II: Implementation of Temperature Maintaining Modifications for Faster Turbine Start-up

This scenario is applicable in the context of improving the start-up times of an already installed steam turbine. One way to achieve this is through the implementation of temperature maintaining measures during cool-down. As a general rule, the warmer the turbine is before start-up, the faster the start-up can be. Previous studies performed at KTH 68 have shown how these modifications can yield up to 4.7% improvements in the annual yield of a CSPPs. The temperature maintaining modifications implemented in this work consisted of electric heating blankets (HB) and gland steam temperature increase, which have been proven to be a favorable combination to maintain the temperature of both the rotor and the casing 9. The HBs provide heat to the external surface of the turbine casing underneath the insulation layer while the gland steam is supplied to the inside of the turbine through the seals in order to avoid air ingress to the blade passage. The warming effect of the modifications on the transient thermal behavior of the steam turbine was calculated using a previously developed and validated steam turbine finite element model 10. Furthermore, following the approach presented in ref. 11, the impact on turbine start-up time improvement was parametrized into DYESOPT through the use of contour maps indicating the turbine temperature improvement after a given cool-down corresponding to a certain combination of the modifications.

The implementation of temperature maintaining modifications comes as well with additional costs and penalties on CSPP performance. For the HBs, the operational penalties relate to the parasitic electricity consumption, which was taken into account and subtracted from the improved annual yield of the CSPP as described in ref. 8. In addition, the costs for the blankets were considered to be proportional to the required HB power Q_{HB} . This cost function is shown in Eq. (2), for which the reference costs were obtained from ref. 12.

$$C_{HB}^{CAPEX} = c_{blanket}^{REF} \cdot \left(\frac{Q_{HB}}{Q_{HB}^{REF}}\right) \quad (2)$$

For the gland steam temperature increase, the additional CAPEX assumed were related to increasing the capabilities of the already existing gland steam auxiliary system. For this, the cost function on Eq. (3) was used in order to scale the gland steam reference costs 13 as a function of the nominal gland steam temperature T_{base} and its increased amount ΔT . The influence of the latter in the overall costs and performance of the DSG-STPP will be evaluated in the results section. Furthermore, the operational expenses (OPEX) of the gland steam temperature modification were calculated with Eq. (4), which takes into account the additional heat input to the gland steam, Q_{gland} , the low heating value of the fluid, LHV , the efficiency of the auxiliary boiler, η_{boiler} , to calculate the costs of the additional fuel required by the auxiliary boiler to heat the gland steam to higher temperatures.

$$C_{GLAND}^{CAPEX} = c_{gland}^{REF} \cdot \left(\frac{T_{base} + \Delta T}{T_{base}}\right) \quad (3)$$

$$C_{GLAND}^{OPEX} = c_{fuel} \cdot \frac{Q_{gland}}{LHV_{fuel} \cdot \eta_{boiler}} \quad (4)$$

Scenario III: Service Agreement with Improved Turbine Overhaul Times

This scenario is applicable for the stage in which the power plant is operational and a service agreement has been established between the OEM and the plant operator. The scenario aims to measure the impact of turbine overhaul times on power plant availability and costs. Furthermore, the target is also to understand the potential gain in having a service agreement that allows for better operational flexibility while the cost value of such agreement increases.

The level of detail that the DYESOPT tool has on maintenance aspects corresponds to that of preventive maintenance 3. This method consists on a pre-set maintenance schedule based on the equivalent operating hours (EOH) of the machine. The annual EOH can be calculated as the sum of the annual normal plant operating hours (NOH) and the equivalent operating hours due to turbine starts (EOHs). Even though the actual degradation of the turbine is not within the modeling scope, the inclusion of the EOHs account for the use of the machine due to cycling. The equations for the EOH and EOHs included within DYESOPT have been presented in ref. 14.

For the modeling of this scenario, the modifications made to the DSG-STPP model were performed firstly to the availability factor 14 shown in Eq. (5). The weeks in maintenance, $w_{O\&M}$, for the reference maintenance cycle, $Cycle_{O\&M}^{REF}$, were varied within the range of [14 18] weeks as stated in refs. 1516 affecting the plant availability. As a consequence of varying availability, the annual NOH and the annual yield due to increasing maintenance overhaul times are also affected. On the costs side, the main impact of this scenario is the OPEX related to the contracted service agreement. As such, it was introduced into DYESOPT that the reference service OPEX would vary as a function of the weeks in maintenance and an exponent B , as shown in Eq. (6). The influence of B on the DSG-STPP performance will be evaluated in the results section.

$$f_{avail} = 1 - \frac{w_{O\&M}}{52} \cdot \frac{EOH}{Cycle_{O\&M}^{REF}} \quad (5)$$

$$C_{SERVICE}^{OPEX} = c_{service}^{REF} \cdot \left(\frac{W_{GROSS}}{W_{GROSS}^{REF}} \right) \cdot \left(\frac{w_{O\&M}^{REF}}{w_{O\&M}} \right)^B \quad (6)$$

RESULTS

Once the respective modifications for flexibility were made on the DSG-STPP, simulations of power plant annual performance were made for each scenario. On each case, the flexibility of the plant was varied by means of turbine ramp up rates, levels of temperature maintaining modifications and overhaul times for scenarios I, II and III, respectively. The coming sections show the impact of these variations on the LCOE as a function of the annual NOH increase due the increased power plant flexibility. Additionally, the breakdown corresponding to such LCOE improvements in terms of CAPEX, OPEX and annual electricity production are also shown.

Sensitivity Studies

Scenario I

The sensitivity study related to this scenario was carried out on two parameters. The first parameter was the previously defined $flex$, which has a direct impact on the ramp up rates and the CAPEX of the steam turbine to be procured. The second parameter that was varied was exponent A in order to ponder on the increased costs of a turbine with superior start-up flexibility within the already existing cost function. **FIGURE 4** shows the DSG-STPP costs and performance variations, with respect to the base case, obtained from the sensitivity study of $flex$ and A . The figure displays annual yield, CAPEX and LCOE as a function of annual NOH increase. Since the operational costs were assumed to be the same for all turbines regardless of their start-up flexibility, the OPEX variations in relation to this scenario are not shown.

For the different cases, it can be seen in the figure that the LCOE generally improves with increasing turbine flexibility. This is due to the fact that the annual yield is higher due to the fact that the turbine produces more electricity by starting faster. However, the influence of increasing CAPEX due to higher A , slows down the rate of LCOE improvement towards the more flexible cases. For the most flexible case of $A=1.8$, the LCOE does not improve even though the annual production does. This study suggests that the trade-off between component flexibility and CAPEX can yield overall performance improvements which are of value on the long term perspective of the power plant. These improvements are in the range of 1.5-4% reduction of LCOE for a corresponding 2-3% increase in CAPEX. As such, the EPC should take that into consideration during the procurement process.

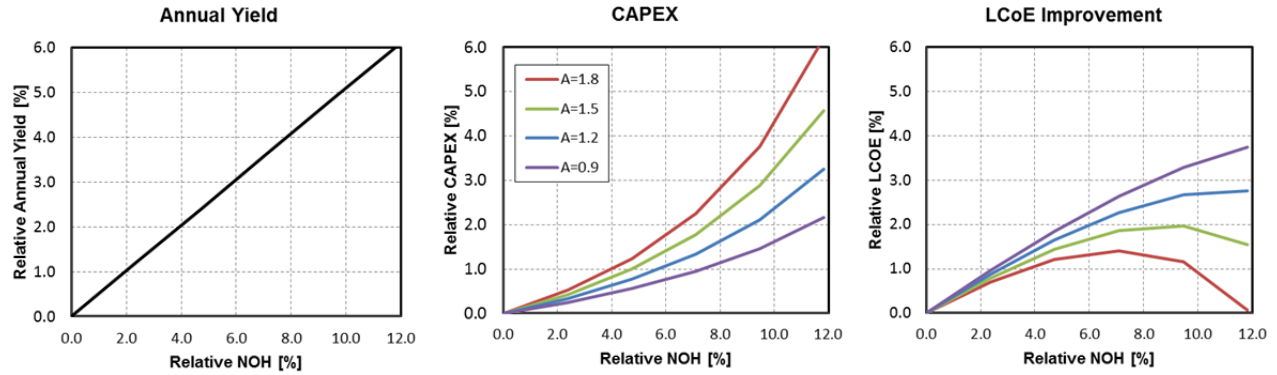


FIGURE 4. Annual yield, CAPEX and LCOE variations from sensitivity of exponent A on scenario I.

Scenario II

The sensitivity related to scenario II was based on the degree of implementation and combination of the turbine modifications. The two modifications, HBs and gland steam temperature increase, can be implemented independently. As such, a first step within this study was to observe the improvements on the annual electricity production as a result of several possible combinations of the modifications. The resulting improvements are shown in the contours of **FIGURE 5** (left). Once having done that, a set of combinations of the measures was selected in order to ensure that the temperatures of both the rotor and the casing are maintained at similar levels for the upcoming start-up; this is denoted in the figure with a red curve.

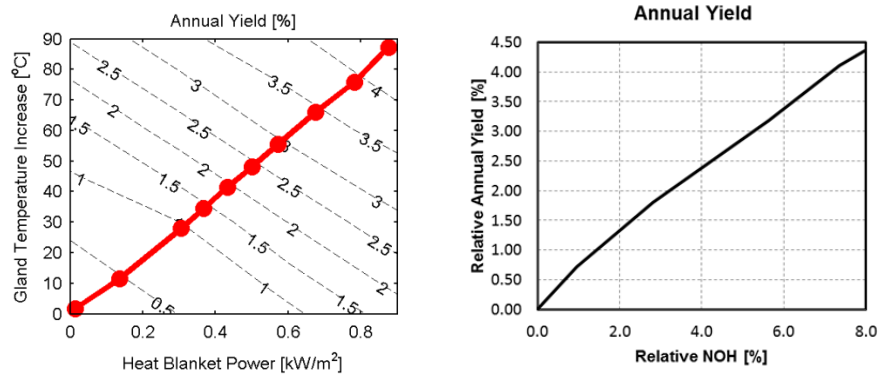


FIGURE 5. Annual yield improvement from sensitivity of temperature maintaining modifications on scenario II.

FIGURE 5 (right) also shows the annual yield resultant from the selected combinations as a function of annual NOH. Analogously, **FIGURE 6** shows the sensitivities of the corresponding CAPEX, OPEX and LCOE improvements. It can be seen in the figures that in this scenario both the CAPEX and OPEX are influenced by increasing turbine flexibility. However, despite of the increasing costs, the annual electricity production improvements are larger and result in LCOE reductions of up to 4%. As such, this scenario shows that temperature maintaining modifications are a practical way to improve power plant flexibility and performance. However, their range of application is limited to not inducing thermal stresses and excessive differential expansion in the turbine..

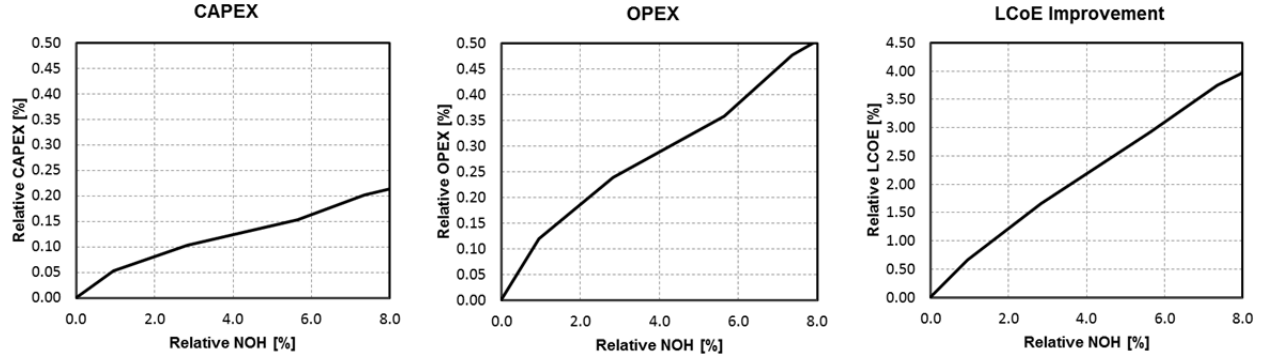


FIGURE 6. CAPEX, OPEX and LCOE variations from sensitivity of temperature maintaining modifications on scenario II.

Scenario III

For scenario III, the sensitivity study carried out was related to weeks for minor and major turbine overhaul and to the exponent B introduced in Eq. (6). In a similar way as in scenario I, the main purpose of the current scenario is to understand whether an increase in OPEX as a trade-off for increased operational availability can be of benefit for the LCOE. **FIGURE 7** shows the resulting relative differences of annual yield, OPEX and LCOE for this scenario. CAPEX was not included since inherently it is not affected by this scenario.

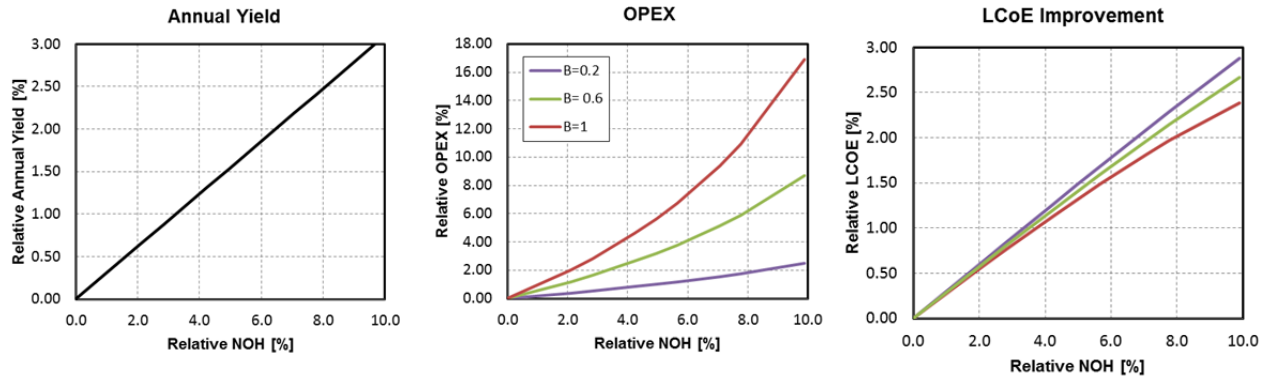


FIGURE 7. Annual yield, OPEX and LCOE variations from sensitivity of exponent B on scenario III.

It can be seen in the figure that although the differences in OPEX become much more significant than those of annual yield, the obtained LCOE improvements are mainly affected by the latter. This is related to their orders of magnitude, CAPEX and annual yield carry more weight than OPEX in the LCOE equation. The results indicate that shortening the time of turbine overhauls can have up to 3% improvements in the annual yield, which translate to LCOE reductions of a similar range. The OPEX increase for the improved maintenance schedules has little effect on the LCOE. However, the actual quality and methods of maintenance does have a strong effect on turbine lifetime. This is not in the scope of this work since this would require detail component models rather than just performance.

Scenario Comparison

The results indicate that that all three scenarios are capable of reaching similar LCOE improvements through different distributions of CAPEX, OPEX and annual yield. As such, in this section the scenarios are compared for similar degrees of CSPP performance improvements. **FIGURE 8** (left) compares the scenarios for the same LCOE improvement while **FIGURE 8** (right) makes the comparison for the same annual NOH. For the case of scenario I and scenario III, the results shown in the figure correspond to that of $A=1.2$ and $B=0.6$, respectively.

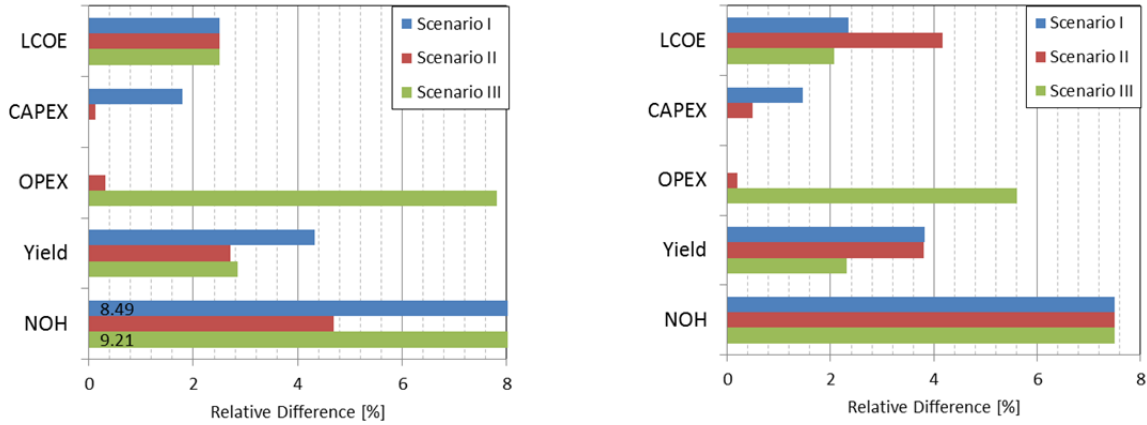


FIGURE 8. Scenario comparison for equal LCOE reductions (left) and annual NOH (right)

For the case of similar LCOE improvements, it can be seen that scenario II has the lowest costs, scenario I has the highest amount of annual electricity yield and scenario III reaches the highest NOH. These aforementioned characteristics are the key aspects of how each scenario accomplishes the same LCOE reduction. For the case of similar NOH, it can be seen that scenario II results in higher LCOE reductions than the other two scenarios. Furthermore, it is seen that while scenario I has the same annual yield improvement as scenario II, its increased CAPEX value results in a lower LCOE improvement. Overall, one affirmation from this comparison would be that scenario II is the most promising one. However, it is important to bear in mind that these scenarios are not mutually exclusive and that they could actually be implemented together. In addition, it is also important to recall that scenarios I and III were subject to the degree of influence of exponents A and B , which directly affect the outcomes.

CONCLUSIONS

This work focused on quantifying the value of operational flexibility in the techno-economic performance of CSPPs. For this, a DSG-STPP model was used as the base case to compare against three scenarios of improved flexibility. Sensitivity studies were carried out for each scenario and then a comparison was made between them for similar levels of CSPP performance improvements. From this work the following conclusions are drawn:

- Component ramp-up rates are an important characteristic to consider at the time of procurement and up to a certain CAPEX increase this choice can influence LCOE reductions of up to 3.87%.
- Implementing temperature maintaining modifications was the most favorable scenario in terms of LCOE reductions at lower costs. However, their range of application of is limited to the turbine design.
- Allowing for higher plant availability through decreasing maintenance turbine stops can yield up to 3% LCOE reductions. However, the costs of such service agreement also relates to the quality of preserving the turbine lifetime, which was not captured by the model in this work.
- Operational flexibility can yield up to 4% reductions in the LCOE and the modeled scenarios show that there are different ways of achieving these improvements. Therefore, the results of this study suggest that operational flexibility should be included as an important objective in the design, construction and operation of CSPPs.

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